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PART II. STEAM RESEARCH PROGRAM.

BY

LEIGHTON B. SMITH, FREDERICK G. KEYES AND HAROLD T. GERRY.

(Continued from page 3 of cover.)

VOLUME 69.

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2. BARNETT, S. J.—The Rotation of Cobalt and Nickel by Magnetization and the Gyromagnetic Ratios of their Magnetic Elements. pp. 119–135. January, 1934. $0.45.
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THE VAPOR PRESSURE OF WATER.

Part II. Steam Research Program.

By

Leighton B. Smith, Frederick G. Keyes and Harold T. Gerry.

(Contribution from the Research Laboratory of Physical Chemistry, Massachusetts Institute of Technology, No. 300.)

THE VAPOR PRESSURE OF WATER.

PART II. STEAM RESEARCH PROGRAM.[1]

BY

LEIGHTON B. SMITH, FREDERICK G. KEYES AND HAROLD T. GERRY.

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THE measurements reported in the present paper were obtained by the so-called static method wherein a mass of fluid in a two-phase condition is confined at constant temperature and the pressure observed. Measurements by the dynamic method, where the fluid is moving continuously, have recently been published by A. Egerton and G. S. Callendar[2] who carried out measurements from 170° C to 374° C. Quite recently also our colleagues in the steam research program sponsored by the American Society of Mechanical Engineers, have published the results of vapor pressure measurements obtained by the static method at the United States Bureau of Standards.[3] There are therefore available the results of three new and independent investigations of water vapor pressures, one by the dynamic or continuous flow method and two by the static method. The vapor pressure values by both methods should be identical up to the point where, in the dynamic method, the flow becomes sufficiently rapid to influence or interfere with the rate of attainment of equilibrium of the molecules of vapor and liquid at constant temperature. The comparisons to be effected in a later section show that the final results of all three investigations are in remarkably good accord.

The results of the measurements at the Research Laboratory of Physical Chemistry have been presented at the Autumn meetings of the steam research group during the time of the regular A. S. M. E. meetings and published usually in the February issue of Mechanical Engineering.[4] The first report of vapor pressure values was in Decem-

[1] The present paper is the second of a series of papers reporting the results of the Massachusetts Institute of Technology program of steam research promoted by the American Society of Mechanical Engineers through the material support of the steam power industries.

[2] A. Egerton and G. S. Callendar, Phil. Trans. Roy. Soc. London *231*, 147 (1932).

[3] N. S. Osborne, H. F. Stimson, E. F. Fioch and D. C. Ginnings, Bur. Stan. Jour. of Research, *10*, 155 (1933).

[4] Mech. Eng. *48*, 153 (1926).

ber 1925 and in the intervening time measurements of the pressure, volume and temperature for the two phase states, the homogeneous liquid and homogeneous gaseous state, have been presented regularly at the annual meetings. During the whole course of the investigation improvements in apparatus and technique developed, but an item of the greatest importance was the choice of container material. This has already been discussed in the preceding paper, Part I of the series, but a brief reference to the container is desirable in the present paper if only to emphasize the wholly satisfactory behavior of the 18 percent chromium, 8 percent nickel steel (trade name Nirosta) used at M. I. T. in the last years of the steam investigation. A similar alloy containing 4.5 tungsten has been found equally satisfactory by Nathan S. Osborne and his coworkers at the U. S. Bureau of Standards.

The measurements of vapor pressure made up to March 1930 were critically examined and smoothed by adjusting consecutive differences of the logarithms of the pressures and a table was prepared for each degree centigrade.[5] A table of derivatives was also prepared by a very convenient method of computation due to Rutledge.[6] The M. I. T. values of pressure were in fair agreement with the values of the Reichsanstalt[7] corrected to the international platinum resistance temperature scale[8] to 300° C. Above the latter temperature the Reichsanstalt values appeared increasingly low by comparison and at 370° C. the difference amounted to 1 in 750.

During 1930 containers of the Chrome-nickel steel had become available and measurements of the volumes of superheated steam were in progress. It was not, however, until 1932 that a systematic series of new measurements on vapor pressures was carried out using the new steel for the container and an apparatus especially designed for the work. The new data proved to be more consistent than the earlier results and, moreover, in good agreement with those of our colleagues at the Bureau of Standards. The agreement with the data of Egerton and Callendar is also excellent.

The Temperature Measurements.

The older series of measurements were made with a platinum electrical resistance thermometer[9] constructed in 1920 of inferior wire.

[5] F. G. Keyes and L. B. Smith, Mech. Eng. *53*, 132 (1931).

[6] G. Rutledge, Jour. Math. and Phys. M. I. T. *8*, 1 (1929). Phys. Rev., *40* 262 (1932).

[7] Int. Crit. Tables III, p. 233.

[8] G. K. Burgess, Bur. Stand. Jour. of Res. *1*, 635 (1928).

[9] See Part I, p. 523.

It was not until the end of 1923 that wire having a temperature coefficient of 0.00392 or greater became available. Thus the early measurements were made with an unsatisfactory resistance thermometer whose indications were, however, finally determined in relation to a thermometer constructed of satisfactory platinum. Unfortunately the comparisons could not be made of the identical thermometer used in the vapor pressure measurements but with one of the same construction and wire. The temperatures in the vapor pressure measurements herein recorded, and in fact all the steam work, are those indicated directly or indirectly through suitable comparisons by a potential terminal type platinum resistance thermometer,[10] No. 4BS, having a temperature coefficient of 0.00392228 and δ constant 1.4965. In the last series of measurements made in 1932 using Nirosta steel and subsequent to 1926, the measurements of temperature were all directly indicated by thermometer No. 4BS.

The calibration of the resistance thermometers was carried out by using the ice and normal boiling temperature of water and the normal sulphur boiling temperature assumed to be 444.6. The latter fixed points reproduce the international temperature scale when platinum of the requisite purity is used. The ice point resistance was observed many times during the course of all the steam work and varied by a few units of 10^{-4} ohms in the course of six years. The type of steam point apparatus employed embodies all the features required to give reproducible and exact results when operated against the atmospheric pressure. Readings in the course of several years were consistent to $\pm$ 0.0013° and show a maximum deviation of 0.002°. The sulphur point apparatus is of glass electrically heated with elaborate radiation shielding for the thermometer. The readings were consistent to $\pm$ 0.009° with a maximum deviation of 0.013°.*

Taking into consideration the consistency of the calibration data of the thermometers used in the vapor pressure measurements combined with general laboratory experience with dozens of platinum resistance thermometers constructed in this laboratory during the past twenty years we believe that the international scale of temperature as

[10] See Table 3, Part I.

* Further improvement in reproducibility of the boiling point temperature of sulphur has been secured by J. A. Beattie and J. M. Gaines using an "artificial" or controlled atmosphere adjusted closely to 760 mm. pressure. By this means the sulphur boiling temperature can be reproduced to $\pm$ 0.003 when nitrogen is used instead of air in the artificial atmosphere apparatus.

realized should not deviate by more than ± 0.01° C. from the indications of similar thermometers constructed in other laboratories. It is scarcely necessary to state that a thermostated and periodically calibrated bridge was used for all resistance measurements.

The Pressure Gauge.

The particular form of gauge used and the mode of detecting pressure equilibrium has been described in Part I. The sensitiveness of the device is very great and the indication is that the pressure reproducibility during calibration is about one in twenty thousand.[11] Thus at 300° the pressure is 84.78 International atmospheres, which on the basis of the latter precision should be determinable to 0.0042 atmospheres. The rate of change of pressure with temperature at 300° is, however, 1.194 atm. per degree and 0.0042 atm. therefore corresponds to, or would require, a reproducibility of at least 0.0035° in the temperature scale. The latter number, however, is less than the reproducibility of the temperature scale since the sulphur boiling point determinations may actually deviate by as much as 0.013 degrees. Taking 0.01° as the temperature scale reproducibility it appears that one in seven thousand should be approximately the agreement between independent observers at 300° and this proves to be, roughly, the order of agreement attained at this temperature by the recent independent investigators. As the reproducibility of the temperature scale is improved the possibility of greater accord seems in prospect.

The gauge No. 52 whose constant was about 0.5 mm. per gram (actually 0.49681 mm. per gram, July, 1932) was used during 1932 in the measurements at the lower pressures and it was sensitive to a fraction of a gram. Gauge No. 28 whose constant was 1.99770 mm. per gram in June, 1931, was used for all pressures in excess of 20 atm. Gauge No. 1T having a constant 1.01443 in July, 1923, was likewise used in measurements up to March 1931.

All weights applied to the piston gauge during calibration or for pressure measurements were compared with standard weights certified by the U. S. Bureau of Standards. The resulting corrections to the weights were computed to give the correct relation to the international kilogram when used in air at 76 cm. and 25° C. The variation of the air density from that corresponding to the latter pressure and temperature was neglected since in Cambridge the extremes of pres-

[11] F. G. Keyes and Jane Dewey, Jour. Opt. Soc. Am. *14*, 491 (1927).

sure are rarely greater than ± 1 cm. from 76 cm. The weight of the piston and all necessary parts, scale pan, etc., contributing to the force exerted on the piston were also similarly determined in terms of the international kilogram. In reducing the pressure observations it was of course necessary to know the relation of the value of gravity at the place where the gauge was used to the standard value of gravity 980.665 cm./sec.^{2} The value of gravity at this laboratory is 980.397 and depends on observations made at the Harvard Observatory nearby. The known thermal dilation of steel suffices to compute the temperature correction of the gauge when the temperature of the latter differs from 30° C, the temperature at which all piston gauge constants is referred.

The piston-cylinder of the R. L. P. C. type of pressure gauge is of hardened steel and exhibits a slow diminution of the effective area with time. Numerical data for the effect is contained in Table IV, Part I, and data for a number of gauges has been published elsewhere.[12] The actual change of the constant with time was largest for the case-hardened No. 1T piston, and during about eight years the change per year of the constant diminished from 0.0182 percent to 0.0165 percent. The constant of the uniformly hardened piston and cylinder of No. 28 gauge increased by 0.0122 percent per year during about four years while the constant of No. 52 gauge having the largest effective diameter (1.37 cm.) increased at a umiform rate of 0.0091 percent per year over about five years. The increase in the gauge constant with time has been found by Dr. Beattie and his collaborators to have essentially the same value for gauges in continuous use and for gauges used only as standards, consequently the "wear" of the piston-cylinder has no connection with the ageing effect. The time rate of change of the constant was of course given consideration in the reduction of all pressure readings.

It is apropos to refer to the convenience of the carbon dioxide vapor pressure at the ice point,[13] 34.4009 ± 0.0013 International atmospheres, as a pressure calibration standard. The latter value found by Bridgeman has recently been confirmed by the measurements of C. H. Meyers and M. S. Van Dusen[14] who give 34.3974 International atmospheres for the vapor pressure of carbon dioxide at zero degrees.

[12] J. A. Beattie and O. C. Bridgeman, Ann. d. Phys. (5) *12*, 827 (1932).

[13] O. C. Bridgeman, J. Am. Chem. Soc., *49*, 1174 (1927).

[14] C. H. Meyers and M. S. Van Dusen, U. S. Bur. of Stand. Jour, of Res. *10*, 391 (1933).

Carbon dioxide is easy to prepare in a state of purity, and the ice point, without excessive precautions, can be reproduced to 0.002° C corresponding to about one in twenty thousand in the pressure. Once the apparatus for pressure calibrations is available the determination of a gauge constant can be carried out in a small fraction of the time required where a mercury column is used.

Constant Temperature Bath.

The temperature bath at the beginning of the steam work in 1922 was not capable of being automatically regulated to constancy of temperature better than ± 0.01°. By 1926, however, the regulation had been improved to ± 0.002°, and further refinement was not sought. The lithium, sodium, potassium nitrates mixture was unsuitable for measurements lower than 140° C and no measurements made below 150° C are recorded. The bath was used to 460° C and was entirely satisfactory in its operation at this temperature.

It was comparatively easy to adjust the energy applied at a value whereby temperature regulation would automatically be maintained at round temperatures. Thus all observations of vapor pressures and other properties were made for the most part at even ten degree intervals beginning with 150° C as indicated by thermometer No. 1 or No. 4 BS. The uniformity of the temperature of the bath is attested to by the constancy of temperature finally attained in 1926, namely ± 0.002° C. Exploration of the bath with respect to the temperature of different portions also indicated that extreme variations were not sensibly greater than 0.002°. The thermometer during measurements was of course actually placed near the water container.

Experimental Procedure.

The method of preparing air free water and introducing the latter into the containers has already been described in Part I. It is now believed that possibly some gas evolution may have resulted by the interaction of water and nickel at the higher temperatures. The design of the apparatus permitted a variation of the relative volumes of vapor and liquid up to the point of complete collapse of the vapor phase, and in the course of the measurements of vapor pressure successive readings were taken with diminishing vapor volumes. No significant rise in vapor pressures was observed, but the procedure may not be sufficiently sensitive as a test for permanent gas when a large quantity of liquid water is present.

The design of apparatus, Fig. 18, Part I, used with the Nirosta container, No. 3 B, in 1932 permitted the convenient expulsion by evaporation of part of the water sample between measurements as well as the collapsing of the vapor phase. As a result of our experience we believe that no permanent gas is generated at temperatures as high as 460° C when the 18 percent–8 percent chrome-nickel alloy steel is used for the containers.

The determination of the oil, mercury and water levels is of great importance in reducing the observations. The determination of the levels differed in detail, however, according to the apparatus used. The early measurements wherein the No. 1 container of nickel was used involved a variable mercury column dependent on the setting or position of the piston of the volumnometer. (See Fig. 9, Part I.) This is likewise the case when the spherical container No. 2 or No. 2 B is used but in the latter case the levels of the mercury actually in the spherical portion of the container was computed from the setting of the volumnometer which measured the amount of mercury injected into the container. The vertical height of mercury in the sphere designated by x is thus determined for a given volume, V, of mercury injected, by the formula $V = 1/3\ \pi\ x^2\ (3r - x)$ where r is the radius of the sphere. The uniform bore of the riser G was determined and the volumes of the connecting portions at the end of G were likewise ascertained. It was therefore possible to determine the level of mercury in G relative to the insulated needle tip at H from the reading of the volumnometer I.

From Fig. 9 it is clear that water levels and oil levels must also be determined. The pressure effect of the oil column is substantially constant since the position of the piston of the gauge when in use was maintained at a fixed point and the density variation of the oil with pressure is small. The part of the water column in the container where water is the confining fluid varies greatly in density and must be computed from a knowledge of the total mass of water in the system, the internal diameter of the container, and the densities of the vapor and liquid phases of water. With these data it is possible to compute the container water level at any temperature and pressure from the reading of the volumnometer. The capillary connecting tube contains water at the temperature of the bath, at the graded temperature between the level of the bath fluid and the bath cover at the temperature of the surrounding air and at 30°. Besides this attention must be given to the column of water in the riser G, Fig. 9. The data

required for computing the pressure effects of all parts of the water column was either known or determined during the course of preparing the apparatus for a series of measurements. The pressure effect of the column of vapor in the container was also computed in deducing the pressure at the surface of separation of the liquid phase and the vapor phase.

In the case of the apparatus, Fig. 18 Part I, the level of mercury in the riser G contributed nothing to the pressure within container E. The volumnometer did, however, enable the water level within container E, of known internal diameter, to be determined with precision even though the exact mass of water within E was unknown. Thus the distance between the inside top of E and the needle point F contacting with mercury in L being known, water may be forced from G into E by means of the volumnometer I. This is continued until, from the rise in pressure, E is known to be completely filled with water. On withdrawing the piston of the volumnometer the exact volume of water vapor space within E may be computed using the known values for the density of water. Since the internal diameter of E is known the distance between the water level and the top of E may be computed.

The difference in mercury levels in L was a small fraction of a millimeter and very easily determined. The oil level between J and the bottom of the gauge piston was likewise easily determined and from its known density as a function of pressure and temperature it was possible to compute the oil line pressure contribution.

Results of the Measurements.

All of the results of our efforts to measure the saturation pressure of water are tabulated in Tables 1, 2 and 3, classified as series 1, series 2 and series 3. In the first columns of the tables there will be found the date of the observations; in the second the container type is designated in accordance with the designations of Table II, Part I; in the third the temperature is given and the thermometer designated, while the fourth column contains the measurements corrected to give the pressure (in International Atmospheres)* of saturated vapor at the contact of the liquid phase within the container. Under each group of data p_m designates the arithmetical average of the group of ob-

* The International atmosphere is defined as the pressure exerted by a column of mercury 76 cm. in length at 0° (density of mercury 13.5951) subject to gravitational acceleration of 980.665 cm./sec.^{2}.

servations while P_{calc} denotes the pressure computed by means of an equation believed to reproduce with tolerable faithfulness our latest and most satisfactory measurements. The number following Δt is the magnitude of the temperature difference which corresponds to the difference in pressure $p_m - p_{calc}$.

Each datum represents the mean of several independent readings or settings of the pressure gauge and corresponding readings of the temperature deduced from the resistance thermometer bridge. No two readings moreover, at any temperature, correspond to the same ratio of liquid to vapor within the container and in many instances, particularly when No. 3 B container was used, withdrawals of water were made without causing any change in the vapor pressure.

The difference between the pressures p_{calc} and p_m in the first series is relatively large, particularly at the higher temperatures where p_m is consistently greater than p_c beginning with 300°. Below 300° the differences are consistently lower. All the No. 1 series of measurements were made in the nickel container No. 1 or the spherical machinery steel container No. 2 where the water was confined with mercury.* Moreover, a considerable number of the measurements were made before the regulation of the bath was improved in 1926.

The measurements in series 2 were all carried out in the cylindrical 18 chromium-8 nickel or Norosta steel container No. 1 B during the course of the measurement of the liquid and vapor phase volumes. In this series the accord of the p_m values with p_{calc} is much more satisfactory than in series 1 and the average deviation expressed as Δt is 0.0099°. There is, moreover, no particularly consistent drift of p_m relative to p_{calc}.

Series 3 are the final measurements made in the special apparatus using container No. 3 B of Nirosta steel. These values of the vapor pressures, together with similar data of Series 2, were computed to average values and used as a basis for determining the constants of a smoothing function of the form $\log p = f(T)$. The averaging of the two series was carried out in the following way. The average value of the vapor pressure in series 2 was used as a single datum and averaged with the measurements at each corresponding temperature of the series 3. This procedure was adopted because of the fact that the liquid columns in the series 2 measurements involved three liquids and was less simple compared with the series 3 measurements. The

* Correction was made for the vapor pressure of the mercury taking account of the Poynting effect.

averaging procedure adopted evidently amounts to weighting in favor of the series 3 measurements.

A large number of empirical functions to relate the pressure to the temperature were tested and the form selected was as follows where x stands for $(T_c - T)$; p_c, T_c representing the critical pressure and temperature.

$$\log_{10} \frac{p_c}{p} = \frac{x}{T}\left[\frac{a + bx + cx^3 + ex^4}{1 + dx}\right]. \qquad (1)$$

$p_c = 218.167$ Int. atm.; $\log p_c = 2.3387890$; $T_c = (374.11 + 273.16)$,

$a = 3.3463130$, $b = 4.14113 \times 10^{-2}$, $c = 7.515484 \times 10^{-9}$,

$d = 1.3794481 \times 10^{-2}$, $e = 6.56444 \times 10^{-11}$.

The constants a, b, c, d, and e were determined using the least square procedure and employing the 27 values of the averaged saturation pressures listed in column 2 of Table 4. The values of the saturation pressure of water at 110, 120, 130 and 140 as given in the International Critical Tables based on the Reichsanstalt values were also included in the least square computing of the constants. The value of the vapor pressure at 100° namely one International atmosphere, was moreover heavily weighted and is exactly given by the formula using the constants tabulated. In Table 4 there will be found a compilation of pressures extending from 100° to the critical temperature for each ten degrees wherein the observed values of the vapor pressures by Egerton and Callendar, by Osborne, Stimson, Fiock and Ginnings, and by the writers are listed together with corresponding values computed with the smoothing functions proposed by the two later groups of investigators. Differences between the results of the three investigations have been listed in columns 7 to 11 and finally the values of dp/dT as computed from the differentiated smoothing equations used by the Bureau of Standards group and the Massachusetts Institute of Technology group.

The differences in the pressures at corresponding temperatures are on the whole small. The differences between the results obtained at the Bureau of Standards by Osborne, Stimson, Fiock and Ginnings and by the authors ($p_{obs.}$ B. S. $-$ $p_{obs.}$ M. I. T.) tend on average to be smaller (mean p_m is 0.01043 atm.) than the average of the differences between Egerton and Callendar's results and the authors' observed pressures (p_m is 0.01953 atm.). The similar average differences for the Osborne, Stimson, Fiock and Ginnings observed pressures and the

Egerton and Callendar observed pressures is 0.01794 atm. The average value of the differences between the authors observed results and the pressures computed with equation 1 amounts to 0.00376 atm. while the similar average of the differences for the Osborne, Stimson, Fiock and Ginnings' observed and computed pressures is 0.00219 atm. or about 42 percent smaller. The average differences for the computed Osborne, Stimson, Fiock and Ginnings pressures and the authors' computed pressures is 0.01327 atm. or somewhat greater than the average of the differences (0.01043 atm.) between the observed pressures. The bulk of the data for all three investigations are in agreement to substantially 4 parts per 10,000; the Osborne, Stimson, Fiock and Ginnings' and the authors' results to roughly 2 parts per 10,000.

A comparison of the three independent investigations on the basis of the differences of temperature corresponding to the pressure differences proves interesting. The data can be readily computed from the values of dp/dT and it is found that Δt_m, the arithmetic mean of the differences, for the Egerton and Callendar results relative to the authors' observed results is 0.01675° C. The similar difference in the case of the authors' observed pressures and those of Osborne, Stimson, Fiock and Ginnings is 0.00973° C. The mean of the temperature differences for the smoothed or computed pressures given by the two American groups of investigators is 0.00823° C. Figure 1 has been prepared by referring the experimental results of the present work, of the Reichsanstalt, of Egerton and Callendar, and of Osborne, Stimson, Fiock and Ginnings to the vapor pressures as computed from Equation 1. A line representing the smoothed values computed by the two equations used by Osborne, Stimson, Fiock and Ginnings is also included. It will be observed that the great bulk of all observations lie within a range of pressure corresponding to $\pm$ 0.02° C.

Table 5 gives the pressures for each degree centigrade from 100° to 374° computed by means of equation 1.

The Critical Temperature and Critical Pressure.

It will be observed that formula 1 contains the critical pressure and the critical temperature. The value for the former quantity 218.167 Int. Atm. was obtained through a graphical investigation of the relation between pressure and temperature in the critical region using 374.11° C as the critical temperature. The latter value was selected on the basis of observations of pressure and volumometer settings (the latter are proportional to the volumes of water in the container)

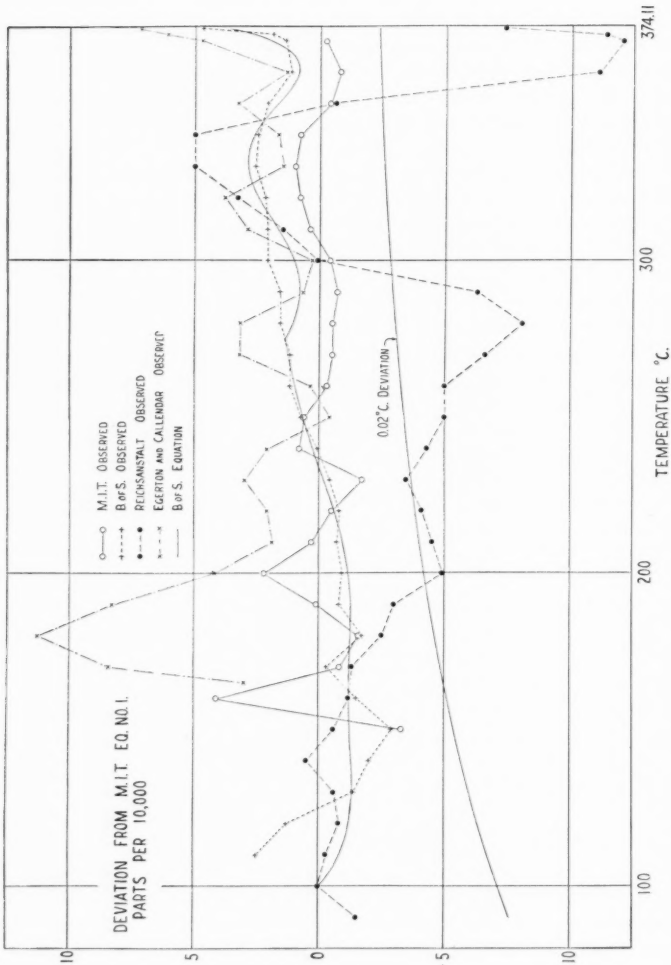
M.I.T. OBSERVED
B. of S. OBSERVED
REICHSANSTALT OBSERVED
EGERTON AND CALLENDAR OBSERVED
B. of S. EQUATION
0.02°C. DEVIATION
DEVIATION FROM M.I.T. EQ. NO. I.
PARTS PER 10,000
10
5
0
-5
-10
100
200
300
374.11
TEMPERATURE °C.

FIGURE 1.

along isothermals below and above 374. The graph of the data is identical with the figure 3 (p. 966) of L. Holborn and A. Baumann's[15] paper of 1910 which lead to the selection of 374° C as the critical temperature.*

Our isotherms are remarkably similar to the isotherms obtained by the authors of the above paper, but we are led to conclude that the critical isotherm is slightly higher, 374.11° C. We doubt that the latter value is exact to better than 0.1° because of insensitiveness inherent in the method. The true value may be slightly higher than the latter temperature but our experience to date indicates that it is certainly not lower. The critical values 218.167 Int. atm. and 374.11° C may be regarded as consistent but probably not final.

The choice of a formula relating the pressure to the temperature wherein a certain pressure and temperature, $p_c = 218.167$ and $t_c = 374.11$, enter in such a manner that all lower values of the saturation pressure and temperature must lie on a curve passing through p_c, t_c may be undesirable. However, no distortion of the values below p_c and t_c will result if p_c and t_c are really consistent with the lower values or lie on a smooth curve with the latter. Pains were accordingly taken to determine p_c with care by graphical means using all available data below the selected temperature 374.11°. The constant p_c could of course have been left to play the role of an undetermined constant but the additional labor involved in carrying out the least square computation did not appear warranted until additional information relative to the critical temperature becomes available.

The Change of Pressure with Temperature.

Exact values of dp/dT are of great importance in making computations involving comparisons between measured quantities and similar quantities based on deduction from the two principles of thermodynamics. The derivative may be obtained by differentiation of the smoothing function, or the pressures, smoothed by the method of adjusted differences, may be submitted to computation, as for example by the very convenient method of Professor George Rutledge.[6] In Table 4, as already stated, the values in the next to the last column have been computed by the equation resulting from the differentiation

[15] L. Holborn and A. Baumann, Ann. der Phys. *31*, 945 (1910).

* The normal sulphur boiling point was taken at 445° C by Holborn and Baumann. Using 444.6° C the critical temperature would be about 0.3° lower or 373.7° C.

of equation 1. The values in the adjacent column are similar values computed by Osborne, Stimson, Fioch and Ginnings from their smoothing equation. The accord between the two sets of derivatives is excellent to 360° when consideration is given to the considerable difference in the forms of the smoothing function used in computing the values.

At 360° the difference between the two computed derivatives amounts to 2.9 parts per 10,000 but the difference at 370° has changed sign and amounts to 27 parts per 10,000 while at 374° the difference has grown to 50 parts per 10,000. In Fig. 2 a graphical representation is

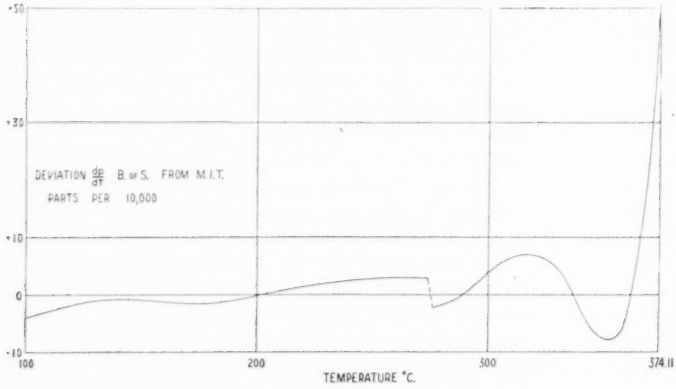

FIGURE 2.

given wherein the values of dp/dT from the U. S. Bureau of Standards equations is related to the derivatives computed from the differentiated Equation 1. The break in the curve occurs at the temperature where a shift is made from the low pressure equation of Osborne, Stimson, Fioch and Ginnings to the high pressure equation.

Table 6 gives the values of dp/dT for each degree centigrade from 100° to 374° computed by means of the differentiated equation based on equation 1.

THE SATURATION PRESSURES BELOW 100° C.

The experimental values of the vapor pressure of water below 100° are not believed to be in need of revision. Thus if vapor pressures are computed by means of equation (1) at 90, 80, 70, 60, 50 degrees, it will

be found that values result which are in excellent agreement with the values given in the Reichsanstalt Wärmetabellen edition of 1916. Moreover using the data in the latter table for each 10° from 10° to 100° for determining the constants of equation 2 by least square computation, it is found that the value of the pressures computed at 110, 120, 130, 140, 150 degrees are in excellent accord with the Reichsanstalt measurements at these temperatures and also the recent results by Osborne, Stimson, Fioch and Ginnings. In a word the values from 10° to 90° are entirely consistent with the new measurements above 100° and may be accepted with confidence. Table 7 gives the pressures for each five degrees, computed by equation (2), by equation (1) and derivatives computed by the respective smoothing equations.

Vapor Pressure Equation for Water 10° to 150° C.

$$\log_{10} \frac{p_c}{p} = \frac{x}{T}\left[\frac{a + bx + cx^3}{1 + dx}\right] \tag{2}$$

$$\log p_c = 2.3387890 \text{ for atm.}$$

$$= 5.2196026 \text{ for mm.}$$

$a = 3.2437814$ $\qquad b = 5.86826 \times 10^{-3}$

$c = 1.1702379 \times 10^{-8}$ $\qquad d = 2.1878462 \times 10^{-3}$

The computed value of the pressure at zero degrees (4.5893 mm.) differs considerably from the "observed" value (4.579 mm.). In fact, the same value (4.579 mm.) at zero degrees is given for both ice and water in the Wärmetabellen. But this is impossible for the normal triple point of water is known to be 0.010°. The value measured at zero degrees was certainly 4.579 mm. as attested to by two separate investigations, but it must correspond either to sub-cooled liquid water or to ice. We believe it to be probably the vapor pressure of sub-cooled water at zero degrees.

The computed pressures in Table 7 accord closely with the observed pressures except at 5° and 0°. The pressures are of course becoming so small that a precision of measurement of even 0.001 mm. amounts to 2 parts per 10,000 at 0° but the difference between the observed and computed values (Equation 2) is 22 parts per 10,000; a difference far outside the precision attained by K. Scheel and W. Heuse.[16] The only evident conclusion is that formula 2 is insufficient to give precise

[16] K. Scheel and W. Heuse, Ann. d. Phys. *31*, 715 (1910).

values of pressure below 10° notwithstanding the fidelity with which the formula reproduces the pressures above 10°. Figure 3 gives the differences in parts per ten thousand between the computed (formula 2) and measured values of the pressure.

In the report on the steam research for December 1929 several smoothing formulas were given for the range of vapor pressures from the ice point to the critical pressure.[17] Equation (5) reproduces the

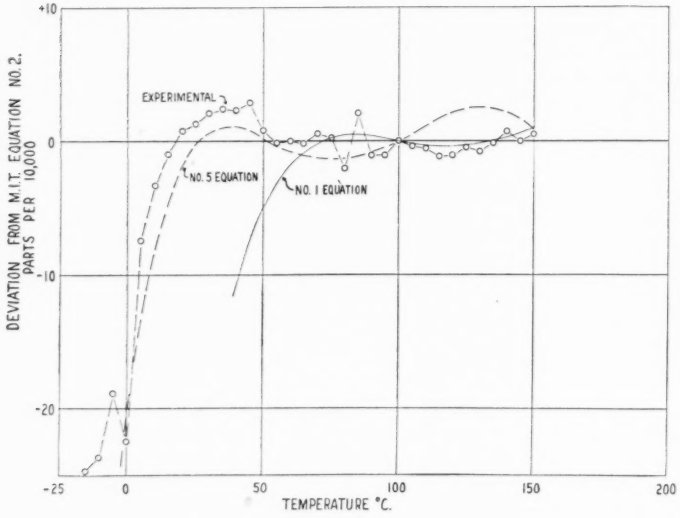

FIGURE 3.

experimental values from zero degrees to 100° with fidelity and is much superior to equation (2) for the range 0 to 10°. The equation is as follows:

$$\log_{10} p = 2.3395111 - \frac{1}{T}(a_0 x + Y \cdot x^2) \qquad (5)$$

$$x = 374.11 - t; \qquad a_0 = 3.4763; \qquad T = 273.13 + t^0\text{C}.$$

$$10^8 \cdot Y = -4.494947 + 2.000419 \cdot 10^{-2} x - 3.593284 \times 10^{-5} x^2 + 3.143572 \cdot 10^{-8} x^3.$$

[17] Mech. Eng. *52*, 125 (1930).

The derivative at 0° computed from the differentiated equation based on (5) is 0.00043816 I. A. as compared with 0.00043806 deduced from the differentiated equation (2). The pressures at 0° are for (5) 4.5798 mm. and for (2) 4.5893 mm. while the experimental value is 4.5790.

The Normal Boiling Temperature of Water.

The most satisfactory mode of using water to establish the 100° reference temperature is undoubtedly to boil the substance in an apparatus whereby the pressure can be kept constantly at 76 cm. The apparatus for the purpose is, however, expensive and exits in few laboratories at present. The common practice of conducting the calibration of thermometers by boiling at the prevailing atmospheric pressure requires a knowledge of the dependence of the boiling temperature upon the pressure. Using Equations (1) and (2) the following formula has been devised, valid from 96° to 103°, whereby suitable corrections can be computed to reduce the observations on the boiling temperature of water at any pressure p to the normal at 760 mm. The pressure p entering the formula implicitly must be corrected to standard gravity 980.665 dynes and the usual corrections for temperture applied to the barometer. The formula follows:

$$\Delta t = 0.0368535\Delta p - 2.0084 \times 10^{-5}\Delta p^2 + 1.714 \times 10^{-8}\Delta p^3$$

$$\Delta p = (p_{corr.\ bar.} - 760) \text{ mm.}$$

TABLE 8.

Δt	Δp	Δt_{calc}
−4	−102.310	−3.99906
−3	−77.873	−2.99978
−2	−52.688	−2.00000
−1	−26.736	−1.00000
0	0	0.00000
+1	27.538	1.00000
+2	55.897	2.00024
+3	85.095	3.00118

The Table 8 indicates that the formula which is consistent with the best present knowledge of the properties of water based on the International Temperature Scale is reliable to better than 0.001° C for several degrees above and below the fixed point 100°.

The authors acknowledge with much pleasure the coöperation of Dr. Robert S. Taylor, who contributed effectively in the work of assembling and perfecting the functioning of the steam apparatus during the early stages of the investigation.

TABLE 1.

Series I—Saturation Pressures of Water in Int. Atm.

Date	Container	Temp. °C.			Press. (Int. Atm.)	
7/15/29	No. 2	150	4 BS		4.705	
				p_{calc}	4.6983	Δt +0.053°
12/30/24	No. 1	160	1		6.103	
1/29/25	No. 1	160	1		6.097	
1/29/25	No. 1	160	1		6.098	
11/4/29	No. 2	160	4 BS		6.095	
7/15/29	No. 2	160	4 BS		6.122	
				p_{mean}	6.1030	
				p_{calc}	6.1007	Δt +0.015°°
1/2/25	No. 1	170	1		7.834	
1/2/25	No. 1	170	1		7.817	
1/20/25	No. 1	170	1		7.813	
11/4/29	No. 2	170	4 BS		7.807	
7/12/29	No. 2	170	4 BS		7.817	
7/13/29	No. 2	170	4 BS		7.830	
7/15/29	No. 2	170	4 BS		7.823	
				p_{mean}	7.8201	
				p_{calc}	7.8180	Δt +0.011°
1/21/25	No. 1	180	1		9.890	
1/21/25	No. 1	180	1		9.908	
11/4/29	No. 2	180	4 BS		9.877	
7/12/29	No. 2	180	4 BS		9.900	
				p_{mean}	9.8938	
				p_{calc}	9.8975	Δt −0.016°
1/27/25	No. 1	190	1		12.374	
1/27/25	No. 1	190	1		12.377	
10/14/29	No. 2	190	4 BS		12.385	
11/4/29	No. 2	190	4 BS		12.373	
7/11/29	No. 2	190	4 BS		12.387	
7/12/29	No. 2	190	4 BS		12.395	
				p_{mean}	12.3818	
				p_{calc}	12.3897	Δt −0.029°
1/28/25	No. 1	200	1		15.331	
4/18/25	No. 1	200	1		15.337	
4/21/25	No. 1	200	1		15.351	
4/21/25	No. 1	200	1		15.321	

TABLE 1—*Continued*

Date	Container	Temp. °C.		Press. (Int. Atm.)		
4/21/25	No. 1	200	1		15.341	
4/22/25	No. 1	200	1		15.344	
5/7/25	No. 1	200	1		15.324	
5/7/25	No. 1	200	1		15.356	
5/8/25	No. 1	200	1		15.343	
5/8/25	No. 1	200	1		15.327	
5/8/25	No. 1	200	1		15.343	
5/11/25	No. 1	200	1		15.316	
10/14/29	No. 2	200	4 BS		15.360	
7/11/29	No. 2	200	4 BS		15.353	
				p_{mean}	15.3391	
				p_{calc}	15.3486	Δt −0.030°
4/23/25	No. 1	210	1		18.816	
4/23/25	No. 1	210	1		18.816	
4/23/25	No. 1	210	1		18.823	
10/18/29	No. 2	210	4 BS		18.820	
7/11/29	No. 2	210	4 BS		18.834	
				p_{mean}	18.8218	
				p_{calc}	18.8314	Δt −0.025°
4/23/25	No. 1	220	1		22.890	
4/24/25	No. 1	220	1		22.887	
4/24/25	No. 1	220	1		22.892	
7/11/29	No. 2	220	4 BS		22.898	
8/16/29	No. 2	220	4 BS		22.895	
				p_{mean}	22.8924	
				p_{calc}	22.8983	Δt 0.013°
4/24/25	No. 1	230	1		27.587	
4/25/25	No. 1	230	1		27.587	
4/25/25	No. 1	230	1		27.597	
7/10/29	No. 2	230	4 BS		27.611	
7/11/29	No. 2	230	4 BS		27.616	
				p_{mean}	27.5996	
				p_{calc}	27.6127	Δt −0.026°
4/27/25	No. 1	240	1		33.002	
4/27/25	No. 1	240	1		33.009	
4/27/25	No. 1	240	1		33.008	
7/9/29	No. 2	240	4 BS		33.021	
7/10/29	No. 2	240	4 BS		32.989	

TABLE 1—*Continued*

Date	Container	Temp. °C.		Press. (Int. Atm.)		
7/16/29	No. 2	240	4 BS		32.997	
7/17/29	No. 2	240	4 BS		33.031	
7/23/29	No. 2	240	4 BS		33.035	
				p_{mean}	33.0115	
				p_{calc}	33.0412	Δt −0.051°
4/28/25	No. 1	250	1		39.228	
4/28/25	No. 1	250	1		39.230	
4/28/25	No. 1	250	1		29.233	
1/29/30	No. 2	250	4 BS		39.228	
1/29/30	No. 2	250	4 BS		39.232	
				p_{mean}	39.2302	
				p_{calc}	39.2536	Δt −0.035°
4/29/25	No. 1	260	1		46.309	
4/29/25	No. 1	260	1		46.313	
2/1/30	No. 2	260	4 BS		46.292	
2/2/30	No. 2	260	4 BS		46.279	
4/29/25	No. 1	260	1		46.303	
				p_{mean}	46.2992	
				p_{calc}	46.3232	Δt −0.032°
4/29/25	No. 1	270	1		54.305	
4/30/25	No. 1	270	1		54.315	
4/29/25	No. 1	270	1		54.317	
				p_{mean}	54.3123	
				p_{calc}	54.3269	Δt −0.017°
4/30/25	No. 1	280	1		63.314	
5/1/25	No. 1	280	1		63.296	
5/1/25	No. 1	280	1		63.326	
				p_{mean}	63.3120	
				p_{calc}	63.3459	Δt −0.035°
5/4/25	No. 1	290	1		73.439	
5/4/25	No. 1	290	1		73.425	
5/4/25	No. 1	290	1		73.424	
				p_{mean}	73.4293	
				p_{calc}	73.4661	Δt −0.034°
7/9/25	No. 1	300	2		84.792	
7/9/25	No. 1	300	2		84.818	

TABLE 1—*Continued*

Date	Container	Temp. °C.	Press. (Int. Atm.)		
7/9/25	No. 1	300 2		84.803	
9/2/25	No. 1	300 2		84.788	
9/2/25	No. 1	300 2		84.791	
			p_{mean}	84.7984	
			p_{calc}	84.7794	Δt +0.016°
9/8/25	No. 1	310 2		97.407	
9/8/25	No. 1	310 2		97.416	
9/8/25	No. 1	310 2		97.420	
2/25/28	No. 1	310 4 BS		97.446	
2/27/28	No. 1	310 4 BS		97.450	
6/1/28	No. 1	310 4 BS		97.426	
			p_{mean}	97.4275	
			p_{calc}	97.3854	Δt +0.032°
7/13/25	No. 1	320 2		111.577	
7/13/25	No. 1	320 2		111.566	
7/13/25	No. 1	320 2		111.303	
9/10/25	No. 1	320 2		111.450	
9/10/25	No. 1	320 2		111.446	
9/10/25	No. 1	320 2		111.448	
2/27/28	No. 1	320 4 BS		111.467	
			p_{mean}	111.4653	
			p_{calc}	111.3934	Δt +0.049°
2/28/28	No. 1	330 4 BS		126.975	
2/28/28	No. 1	330 4 BS		127.000	
4/5/28	No. 1	330 4 BS		127.010	
			p_{mean}	126.9950	
			p_{calc}	126.9265	Δt +0.042°
7/15/25	No. 1	340 2		144.382	
7/15/25	No. 1	340 2		144.383	
7/15/25	No. 1	340 2		144.373	
9/18/25	No. 1	340 2		144.296	
9/18/25	No. 1	340 2		144.298	
10/21/26	No. 1	340 4 BS		144.312	
10/21/26	No. 1	340 4 BS		144.333	
2/28/28	No. 1	340 4 BS		144.191	
			p_{mean}	144.3210	
			p_{calc}	144.1278	Δt +0.107°

TABLE 1—*Continued*

Date	Container	Temp. °C.		Press. (Int. Atm.)		
6/9/26	No. 1	350	4 BS		163.357	
6/9/26	No. 1	350	4 BS		163.356	
6/9/26	No. 1	350	4 BS		163.366	
6/9/26	No. 1	350	4 BS		163.373	
6/30/26	No. 1	350	4 BS		163.322	
6/30/26	No. 1	350	4 BS		163.327	
6/30/26	No. 1	350	4 BS		163.329	
10/20/26	No. 1	350	4 BS		163.381	
10/20/26	No. 1	350	4 BS		163.383	
10/20/26	No. 1	350	4 BS		163.414	
10/20/26	No. 1	350	4 BS		163.213	
				p_{mean}	163.3474	
				p_{calc}	163.1704	Δt +0.088°
9/23/25	No. 1	355	2		173.638	
9/23/25	No. 1	355	2		173.643	
				p_{mean}	173.6405	
				p_{calc}	173.4485	Δt +0.091°
6/11/26	No. 1	360	4 BS		184.469	
6/11/26	No. 1	360	4 BS		184.478	
6/11/26	No. 1	360	4 BS		184.498	
6/29/26	No. 1	360	4 BS		184.446	
6/29/26	No. 1	360	4 BS		184.447	
10/21/26	No. 1	360	4 BS		184.387	
10/21/26	No. 1	360	4 BS		184.410	
10/21/26	No. 1	360	4 BS		184.411	
4/5/27	No. 1	360	4 BS		184.362	
4/5/27	No. 1	360	4 BS		184.355	
				p_{mean}	184.4263	
				p_{calc}	184.2744	Δt +0.068°
6/14/26	No. 1	365	4 BS		195.763	
6/14/26	No. 1	365	4 BS		195.829	
				p_{mean}	195.7960	
				p_{calc}	195.6895	Δt +0.045°
6/15/26	No. 1	370	4 BS		207.855	
6/15/26	No. 1	370	4 BS		207.845	
6/16/26	No. 1	370	4 BS		207.924	
				p_{mean}	207.8747	
				p_{calc}	207.7414	Δt +0.054°

TABLE 1—*Continued*

Date	Container	Temp. °C.	Press. (Int. Atm.)		
6/21/26	No. 1	371 4 BS	210.361		
6/21/26	No. 1	371 4 BS	210.353		
6/21/26	No. 1	371 4 BS	210.346		
6/21/26	No. 1	371 4 BS	210.343		
6/22/26	No. 1	371 4 BS	210.350		
			p_{mean}	210.3506	
			p_{calc}	210.2332	Δt +0.047°
6/23/26	No. 1	372 4 BS	212.878		
6/23/26	No. 1	372 4 BS	212.884		
6/23/26	No. 1	372 4 BS	212.886		
			p_{mean}	212.8827	
			p_{calc}	212.7535	Δt +0.051°
6/25/26	No. 1	373 4 BS	215.491		
6/25/26	No. 1	373 4 BS	215.479		
6/25/26	No. 1	373 4 BS	215.529		
			p_{mean}	215.4997	
			p_{calc}	215.3027	Δt +0.077°
6/28/26	No. 1	374 4 BS	218.191		
6/28/26	No. 1	374 4 BS	218.211		
6/28/26	No. 1	374 4 BS	218.191		
7/9/26	No. 1	374 4 BS	218.142		
7/9/26	No. 1	374 4 BS	218.170		
7/9/26	No. 1	374 4 BS	218.209		
7/10/26	No. 1	374 4 BS	218.165		
7/10/26	No. 1	374 4 BS	218.243		
7/10/26	No. 1	374 4 BS	218.236		
			p_{mean}	218.1953	
			p_{calc}	217.8815	Δt +0.121°

TABLE 2.

Series II—Saturation Pressures of Water in Int. Atm.

Date	Container	Temp. °C.	Press. (Int. Atm.)		
5/11/32	No. 1 B	200 4 BS	15.340		
5/11/32	No. 1 B	200 4 BS	15.339		
5/12/32	No. 1 B	200 4 BS	15.340		
5/13/32	No. 1 B	200 4 BS	15.338		
5/13/32	No. 1 B	200 4 BS	15.342		
			p_{mean}	15.3398	
			p_{calc}	15.3486	Δt −0.027°

TABLE 2—*Continued*

Date	Container	Temp. °C.		Press. (Int. Atm.)		
5/13/32	No. 1 B	260	4 BS		46.316	
5/16/32	No. 1 B	260	4 BS		46.312	
5/16/32	No. 1 B	260	4 BS		46.316	
				p_{mean}	46.3147	
				p_{calc}	46.3232	Δt −0.011°
5/16/32	No. 1 B	280	4 BS		63.330	
				p_{calc}	63.3459	Δt −0.017°
5/16/32	No. 1 B	300	4 BS		84.767	
5/17/32	No. 1 B	300	4 BS		84.765	
				p_{mean}	84.7660	
				p_{calc}	84.7794	Δt −0.011°
5/17/32	No. 1 B	310	4 BS		97.395	
				p_{calc}	97.3854	Δt +0.007°
5/17/32	No. 1 B	320	4 BS		111.402	
				p_{calc}	111.3934	Δt +0.006°
5/17/32	No. 1 B	330	4 BS		126.938	
				p_{calc}	126.9265	Δt +0.007°
5/18/32	No. 1 B	340	4 BS		144.146	
5/18/32	No. 1 B	340	4 BS		144.145	
				p_{mean}	144.1455	
				p_{calc}	144.1278	Δt +0.010°
5/18/32	No. 1 B	350	4 BS		163.165	
				p_{calc}	163.1704	Δt −0.003°
5/18/32	No. 1 B	360	4 BS		184.262	
				p_{calc}	184.2744	Δt −0.006°
5/18/32	No. 1 B	370	4 BS		207.757	
5/18/32	No. 1 B	370	4 BS		207.747	
				p_{mean}	207.7520	
				p_{calc}	207.7414	Δt +0.004°

TABLE 3.

Series III—Saturation Pressures of Water in Int. Atm.

Date	Container	Temp. °C.		Press. (Int. Atm.)		
7/30/32	No. 3 B	150	4 BS		4.6966	
8/1/32	No. 3 B	150	4 BS		4.6968	
				p_{mean}	4.6967	
				p_{calc}	4.6983	Δt −0.013°
7/30/32	No. 3 B	160	4 BS		6.1021	
8/1/32	No. 3 B	160	4 BS		6.1038	
8/2/32	No. 3 B	160	4 BS		6.1038	
				p_{mean}	6.1032	
				p_{calc}	6.1007	Δt +0.016°
7/29/32	No. 3 B	170	4 BS		7.8170	
7/30/32	No. 3 B	170	4 BS		7.8182	
8/2/32	No. 3 B	170	4 BS		7.8169	
				p_{mean}	7.8174	
				p_{calc}	7.8180	Δt −0.003°
7/29/32	No. 3 B	180	4 BS		9.8953	
8/1/32	No. 3 B	180	4 BS		9.8979	
8/1/32	No. 3 B	180	4 BS		9.8945	
				p_{mean}	9.8959	
				p_{calc}	9.8975	Δt −0.007°
7/29/32	No. 3 B	190	4 BS		12.3887	
8/1/32	No. 3 B	190	4 BS		12.3909	
				p_{mean}	12.3898	
				p_{calc}	12.3897	Δt 0.000°
7/11/32	No. 3 B	200	4 BS		15.365	
7/14/32	No. 3 B	200	4 BS		15.352	
7/14/32	No. 3 B	200	4 BS		15.355	
7/14/32	No. 3 B	200	4 BS		15.354	
7/18/32	No. 3 B	200	4 BS		15.352	
7/26/32	No. 3 B	200	4 BS		15.351	
7/27/32	No. 3 B	200	4 BS		15.353	
7/29/32	No. 3 B	200	4 BS		15.3484	
				p_{mean}	15.3538	
				p_{calc}	15.3486	Δt +0.016°
7/18/32	No. 3 B	210	4 BS		18.834	

TABLE 3—*Continued*

Date	Container	Temp. °C.	Press. (Int. Atm.)		
7/26/32	No. 3 B	210 4 BS		18.829	
			p_{mean}	18.8315	
			p_{calc}	18.8314	Δt 0.000°
7/18/32	No. 3 B	220 4 BS		22.902	
7/26/32	No. 3 B	220 4 BS		22.892	
			p_{mean}	22.8970	
			p_{calc}	22.8983	Δt −0.003°
7/26/32	No. 3 B	230 4 BS		27.608	
			p_{calc}	27.6117	Δt −0.007°
7/18/32	No. 3 B	240 4 BS		33.059	
7/19/32	No. 3 B	240 4 BS		33.040	
7/26/32	No. 3 B	240 4 BS		33.035	
			p_{mean}	33.0447	
			p_{calc}	33.0412	Δt +0.006°
7/19/32	No. 3 B	250 4 BS		39.256	
7/26/32	No. 3 B	250 4 BS		39.255	
			p_{mean}	39.2555	
			p_{calc}	39.2536	Δt +0.003°
7/19/32	No. 3 B	260 4 BS		46.323	
7/25/32	No. 3 B	260 4 BS		46.329	
			p_{mean}	46.3260	
			p_{calc}	46.3232	Δt +0.004°
7/19/32	No. 3 B	270 4 BS		54.321	
7/25/32	No. 3 B	270 4 BS		54.327	
			p_{mean}	54.3240	
			p_{calc}	54.3269	Δt −0.003°
7/19/32	No. 3 B	280 4 BS		63.344	
7/25/32	No. 3 B	280 4 BS		63.354	
			p_{mean}	63.3490	
			p_{calc}	63.3459	Δt +0.003°
7/20/32	No. 3 B	290 4 BS		73.455	
7/25/32	No. 3 B	290 4 BS		73.467	
			p_{mean}	73.4610	
			p_{calc}	73.4661	Δt −0.005°

TABLE 3—*Continued*

Date	Container	Temp. °C.	Press. (Int. Atm.)		
7/20/32	No. 3 B	300 4 BS		84.779	
7/25/32	No. 3 B	300 4 BS		84.783	
			p_{mean}	84.7810	
			p_{calc}	84.7794	Δt +0.001°
7/20/32	No. 3 B	310 4 BS		97.381	
7/25/32	No. 3 B	310 4 BS		97.391	
			p_{mean}	97.3860	
			p_{calc}	97.3854	Δt 0.000°
7/20/32	No. 3 B	320 4 BS		111.402	
7/25/32	No. 3 B	320 4 BS		111.401	
			p_{mean}	111.4015	
			p_{calc}	111.3934	Δt +0.005°
7/20/32	No. 3 B	330 4 BS		126.934	
7/23/32	No. 3 B	330 4 BS		126.946	
			p_{mean}	126.9400	
			p_{calc}	126.9265	Δt +0.008°
7/20/32	No. 3 B	340 4 BS		144.131	
7/23/32	No. 3 B	340 4 BS		144.142	
			p_{mean}	144.1365	
			p_{calc}	144.1278	Δt +0.005°
7/21/32	No. 3 B	350 4 BS		163.159	
7/22/32	No. 3 B	350 4 BS		163.168	
			p_{mean}	163.1635	
			p_{calc}	163.1704	Δt −0.003°
7/21/32	No. 3 B	360 4 BS		184.254	
7/22/32	No. 3 B	360 4 BS		184.263	
			p_{mean}	184.2585	
			p_{calc}	184.2744	Δt −0.007°
7/22/32	No. 3 B	370 4 BS		207.721	
			p_{calc}	207.7414	Δt −0.008°

TABLE 4

Comparison of Vapor Pressure Measurements

M. I. T. Equation $\log \frac{p_c}{p} = \frac{x}{T}\left[\frac{a + bx + cx^3 + ex^4}{1 + dx}\right]$

$p_c = 218.167$ atm. Int. $\log p_c = 2.3387890$ $x = t_c - t$ $t_c = 374.11$

$T = t + 273.16$ $a = 3.3463130$ $b = .0414113$ $c = .007515484 \times 10^{-6}$

$d = .013794481$ $e = .00656444 \times 10^{-8}$

$t°$ C.	Mean Observed p M. I. T.	Calculated p M. I. T.	Mean Observed p B. S.	Calculated p B. S.	Egerton & Callendar Obs. p
100		1.000000			
110	1.4139*	1.41395	1.4143	1.4138	
120	1.9595*	1.95954	1.9598	1.9593	
130	2.6662*	2.66616	2.6658	2.6658	
140	3.5669*	3.56683	3.5661	3.5664	
150	4.6967	4.69826	4.6969	4.6977	
160	6.1032	6.10071	6.0998	6.1000	
170	7.8174	7.81802	7.8178	7.8171	7.8246
180	9.8959	9.89745	9.8958	9.8962	9.9086
190	12.3898	12.3897	12.3887	12.3881	12.400
200	15.352	15.3486	15.3472	15.3468	15.355
210	18.832	18.8314	18.8300	18.8296	18.835
220	22.897	22.8983	22.8964	22.8969	22.903
230	27.608	27.6127	27.6117	27.6122	27.621
240	33.044	33.0412	33.0416	33.0421	33.048
250	39.256	39.2536	39.2566	39.2563	39.252
260	46.322	46.3232	46.3286	46.3280	46.325
270	54.324	54.3269	54.3333	54.3339	54.345
280	63.343	63.3459	63.3558	63.3524	63.366
290	73.461	73.4661	73.4779	73.4723	73.471
300	84.776	84.7794	84.7969	84.7881	84.782
310	97.389	97.3854	97.4062	97.4015	97.414
320	111.402	111.3934	111.418	111.420	111.436
330	126.939	126.9265	126.960	126.964	126.946
340	144.139	144.1278	144.167	144.168	144.152
350	163.164	163.1704	163.205	163.200	163.224
360	184.260	184.2744	184.297	184.290	184.299
370	207.737	207.7414	207.771	207.781	207.839
372		212.7535	212.795	212.808	212.883
374		217.8815	217.985	217.958	218.048
374.11	218.167				

* I. C. T. Value used for M. I. T. Obs.

TABLE 4—*Continued*

$t°$ C.	Obs. p M. I. T. $-$Cal. p M. I. T.	Obs. p B. S. $-$Cal. p B. S.	Obs. p B. S. $-$Obs. p M. I. T.	Cal. p B. S. $-$Cal. p M. I. T.	Obs. p E. & C. $-$Obs. p M. I. T.	$\frac{dp}{dT}$ M. I. T.	$\frac{dp}{dT}$ B. S.
100						.035703	.03569
110	−.00005*	+.0005	+.0004*	−.00015		.047517	.04750
120	−.00004*	+.0005	+.0003*	−.00024		.062090	.06208
130	+.00004*	.0000	−.0004*	−.00036		.079784	.07978
140	+.00007*	−.0003	−.0008*	−.00043		.100964	.10095
150	−.00156	−.0008	+.0002	−.00056		.125993	.12598
160	+.00249	−.0002	−.0034	−.00071		.155228	.15521
170	−.00062	+.0007	+.0004	−.00092	+.0072	.189021	.18899
180	−.00155	−.0004	−.0001	−.00125	+.0127	.227711	.22768
190	+.0001	+.0006	−.0011	−.0016	+.0102	.271632	.27161
200	+.0034	+.0004	−.0048	−.0018	+.003	.321106	.32110
210	+.0006	+.0004	−.0020	−.0018	+.003	.37645	.37647
220	−.0013	−.0005	−.0006	−.0014	+.006	.43798	.43805
230	−.0047	−.0005	+.0037	−.0005	+.013	.50601	.5061
240	+.0028	−.0005	−.0024	+.0009	+.004	.58086	.5810
250	+.0024	+.0003	+.0006	+.0027	−.004	.66285	.6630
260	−.0012	+.0006	+.0066	+.0048	+.003	.75235	.7524
270	−.0029	−.0006	+.0093	+.0070	+.021	.84974	.8496
280	−.0029	+.0034	+.0128	+.0065	+.023	.95548	.9553
290	−.0051	+.0056	+.0169	+.0062	+.010	1.07009	1.0701
300	−.0034	+.0088	+.0209	+.0087	+.006	1.19424	1.1947
310	+.0036	+.0047	+.0172	+.0161	+.025	1.32878	1.3297
320	+.0086	−.002	+.016	+.0266	+.034	1.47486	1.4760
330	+.0125	−.004	+.021	+.0375	+.007	1.63413	1.6349
340	+.0112	−.001	+.028	+.0402	+.013	1.80899	1.8086
350	−.0064	+.005	+.041	+.0296	+.064	2.00315	2.0016
360	−.0144	+.007	+.037	+.0156	+.039	2.22264	2.2220
370	−.0077	−.010	+.034	+.0396	+.102	2.47786	2.4846
372		−.013		+.0545		2.53463	2.5542
374		+.027		+.0767		2.59376	2.6068
374.11							

E. & C. = Egerton & Callendar

TABLE 5.

Vapor Pressure of Water Computed by Means of Equation 1.

	0	1	2	3	4	5	6	7	8	9
100	1.0000	1.0362	1.0735	1.1119	1.1515	1.1922	1.2341	1.2772	1.3215	1.3671
110	1.4139	1.4621	1.5116	1.5625	1.6148	1.6685	1.7237	1.7804	1.8385	1.8982
120	1.9595	2.0224	2.0870	2.1532	2.2211	2.2907	2.3621	2.4354	2.5104	2.5873
130	2.6662	2.7469	2.8296	2.9144	3.0012	3.0900	3.1810	3.2741	3.3695	3.4670
140	3.5668	3.6690	3.7734	3.8803	3.9895	4.1013	4.2155	4.3323	4.4516	4.5736
150	4.6983	4.8256	4.9557	5.0886	5.2243	5.3629	5.5045	5.6490	5.7965	5.9470
160	6.1007	6.2575	6.4175	6.5808	6.7473	6.9171	7.0904	7.2670	7.4471	7.6308
170	7.8180	8.0088	8.2034	8.4016	8.6036	8.8094	9.0190	9.2326	9.4502	9.6718
180	9.8974	10.127	10.361	10.599	10.842	11.089	11.340	11.595	11.856	12.120
190	12.390	12.663	12.942	13.226	13.514	13.807	14.105	14.409	14.717	15.030
200	15.349	15.672	16.002	16.336	16.675	17.021	17.372	17.728	18.090	18.458
210	18.831	19.211	19.596	19.987	20.384	20.788	21.197	21.613	22.035	22.463
220	22.898	23.339	23.787	24.242	24.703	25.170	25.645	26.126	26.615	27.110
230	27.613	28.122	28.639	29.163	29.695	30.233	30.780	31.334	31.895	32.464
240	33.041	33.626	34.219	34.819	35.428	36.045	36.670	37.303	37.945	38.595
250	39.254	39.921	40.597	41.281	41.974	42.677	43.388	44.108	44.837	45.575
260	46.323	47.080	47.847	48.623	49.408	50.203	51.008	51.823	52.648	53.482
270	54.327	55.182	56.047	56.922	57.808	58.704	59.611	60.529	61.457	62.396
280	63.346	64.307	65.279	66.262	67.257	68.263	69.280	70.309	71.350	72.402
290	73.466	74.542	75.630	76.730	77.843	78.968	80.105	81.254	82.417	83.592
300	84.779	85.980	87.194	88.421	89.661	90.914	92.181	93.462	94.756	96.064
310	97.385	98.721	100.07	101.43	102.81	104.21	105.61	107.04	108.47	109.93
320	111.39	112.88	114.37	115.89	117.42	118.96	120.52	122.10	123.69	125.30
330	126.93	128.57	130.23	131.90	133.60	135.31	137.04	138.78	140.55	142.33
340	144.13	145.95	147.78	149.64	151.51	153.41	155.32	157.25	159.20	161.18
350	163.17	165.18	167.22	169.27	171.35	173.45	175.57	177.71	179.88	182.06
360	184.27	186.51	188.77	191.05	193.36	195.69	198.05	200.43	202.84	205.28
370	207.74	210.23	212.75	215.30	217.88					

TABLE 6.

Values of dp/dt for Saturated Water Vapor derived brom Equation 1.

	0	1	2	3	4	5	6	7	8	9
100	0.035703	0.036770	0.037862	0.038978	0.040121	0.041288	0.042481	0.043700	0.044945	0.046218
110	.047517	.048844	.050200	.051583	.052995	.054436	.055907	.057407	.058937	.060498
120	.062090	.063713	.065367	.067054	.068772	.070524	.072308	.074126	.075978	.077863
130	.079784	.081739	.083729	.085755	.087817	.089915	.092050	.094222	.096431	.098678
140	.10096	.10329	.10565	.10805	.11049	.11297	.11550	.11806	.12066	.12331
150	.12599	.12872	.13149	.13431	.13716	.14006	.14300	.14599	.14903	.15210
160	.15523	.15840	.16161	.16487	.16818	.17153	.17493	.17838	.18188	.18543
170	.18902	.19266	.19636	.20010	.20389	.20773	.21163	.21557	.21956	.22361
180	.22771	.23186	.23607	.24032	.24463	.24900	.25342	.25789	.26241	.26699
190	.27163	.27632	.28107	.28588	.29074	.29565	.30063	.30566	.31072	.31590
200	.32111	.32637	.33171	.33708	.34252	.34802	.35359	.35921	.36490	.37064
210	.37645	.38232	.38825	.39425	.40030	.40642	.41261	.41885	.42517	.43154
220	.43798	.44449	.45106	.45769	.46440	.47116	.47800	.48490	.49187	.49891
230	.50601	.51318	.52042	.52773	.53511	.54256	.55008	.55767	.56533	.57306
240	.58086	.58873	.59667	.60469	.61278	.62094	.62917	.63748	.64586	.65432
250	.66285	.67146	.68014	.68889	.69773	.70664	.71562	.72469	.73383	.74305
260	.75235	.76172	.77118	.78072	.79034	.80003	.80981	.81967	.82961	.83963
270	.84974	.85993	.87021	.88056	.89101	.90154	.91215	.92285	.93364	.94451
280	.95548	.96653	.97767	.98890	1.0002	1.0116	1.0231	1.0347	1.0464	1.0582
290	1.0701	1.0821	1.0941	1.1063	1.1186	1.1309	1.1434	1.1559	1.1686	1.1814
300	1.1942	1.2072	1.2203	1.2335	1.2467	1.2601	1.2736	1.2873	1.3010	1.3148
310	1.3288	1.3428	1.3570	1.3713	1.3857	1.4003	1.4149	1.4297	1.4446	1.4597
320	1.4749	1.4902	1.5056	1.5212	1.5369	1.5527	1.5687	1.5848	1.6011	1.6175
330	1.6341	1.6509	1.6678	1.6848	1.7020	1.7194	1.7370	1.7547	1.7726	1.7907
340	1.8090	1.8275	1.8461	1.8650	1.8841	1.9033	1.9228	1.9426	1.9625	1.9827
350	2.0031	2.0238	2.0448	2.0660	2.0874	2.1092	2.1313	2.1536	2.1763	2.1993
360	2.2226	2.2463	2.2704	2.2948	2.3196	2.3449	2.3705	2.3966	2.4232	2.4503
370	2.4779	2.5060	2.5346	2.5639	2.5938					

TABLE 7.

VAPOR PRESSURE IN INT. ATM. OF WATER BELOW 100°.

t° C.	$p^{mm.}$	$p^{I.A.}$	$p^{I.A.}$	$\left(\frac{dp}{dt}\right)^{mm.}$	$\left(\frac{dp}{dt}\right)^{I.A.}$	$\left(\frac{dp}{dt}\right)^{I.A.}$
	Eq. 2	Eq. 2	Eq. 1	Eq. 2	Eq. 2	Eq. 1
−15	1.4400	0.001895				
−10	2.1541	0.002834				
− 5	3.1690	0.004170				
0*	4.5893	0.006039		0.3329	0.0004381	
5	6.5479	0.008616		0.4561	0.0006001	
10	9.2121	0.012121		0.6165	0.0008112	
15	12.7893	0.016828		0.8228	0.0010827	
20	17.5336	0.023070		1.0851	0.0014278	
25	23.7530	0.031254		1.4149	0.0018618	
30	31.8172	0.041865		1.8253	0.0024017	
35	42.1647	0.055480		2.3308	0.0030669	
40	55.311	0.072778		2.9479	0.0038788	
45	71.860	0.09455		3.6944	0.0048610	
50	92.503	0.12172	0.12165	4.5898	0.0060392	
55	118.041	0.15532		5.6555	0.0074414	
60	149.380	0.19655	0.19652	6.9141	0.0090975	
65	187.544	0.24677		8.3902	0.0110397	
70	233.687	0.30748	0.30748	10.1094	0.013302	
75	289.094	0.38039		12.099	0.015920	
80	355.175	0.46734	0.46736	14.388	0.018931	
85	433.512	0.57041		17.004	0.022374	
90	525.818	0.6919	0.6919	19.980	0.026290	0.026281
95	633.968	0.8342	0.8342	23.347	0.030720	0.030718
100	760.000	1.0000	1.0000	27.137	0.035706	0.035703
105	906.095	1.1922	1.1922	31.382	0.041292	0.041288
110	1074.63	1.4140	1.4140	36.117	0.047522	0.047517
120	1489.31	1.9596	1.9595	47.191	0.062093	0.062090
130	2026.3	2.6662	2.6662	60.631	0.079777	0.079784
140	2710.7	3.5668	3.5668	76.712	0.10094	0.10096
150	3570.3	4.6977	4.6983	95.707	0.12593	0.12599

*Sub-cooled water, triple point 0.01° C.